Decision aid methodologies in transportation

Lecture 2: Aircraft Scheduling

Prem Kumar

prem.viswanathan@epfl.ch

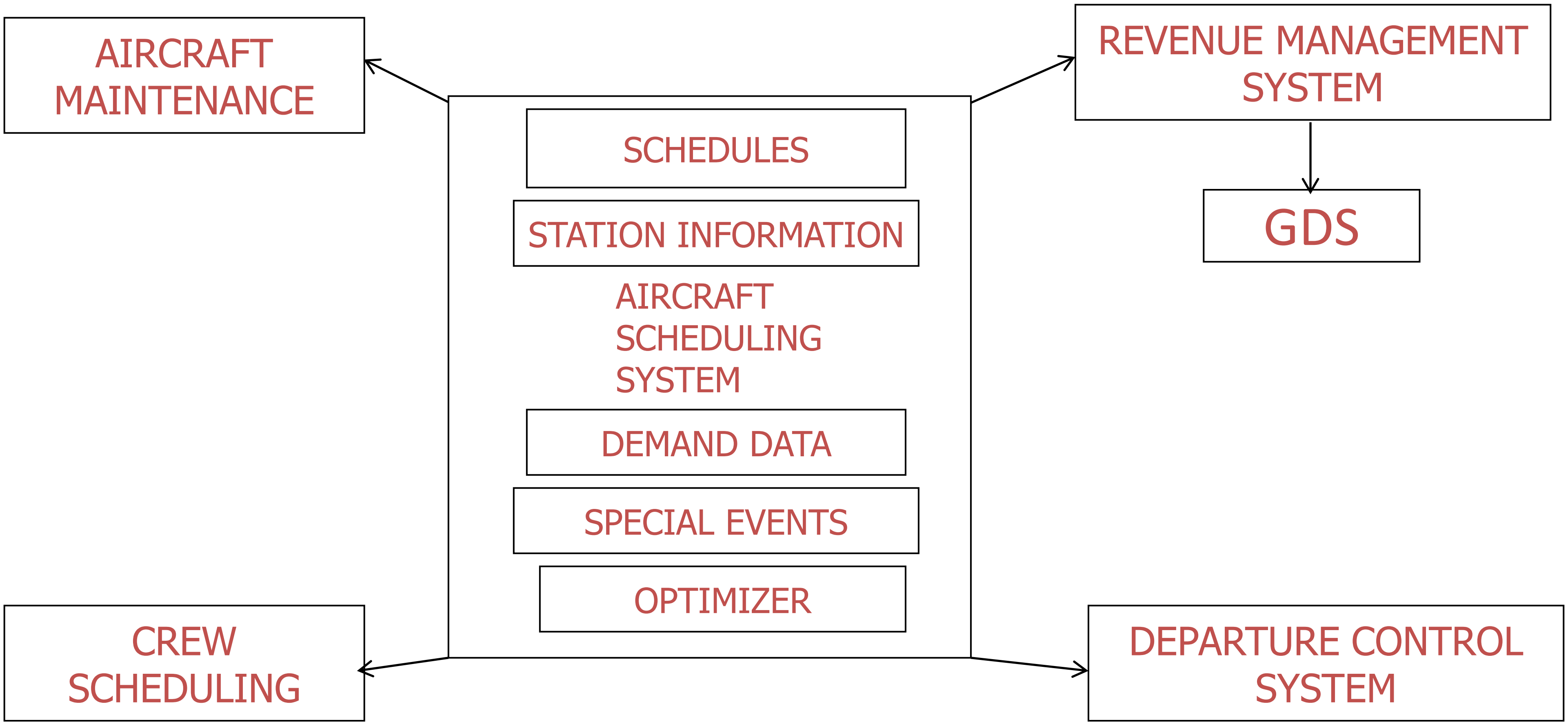
Transport and Mobility Laboratory

This course is an extension of the same course taught last year by Dr Niklaus Eggenberg.
A few slides are inspired from the material used by him and Prof C Barnhart (MIT Courseware)

Summary

- Aircraft Scheduling in central to all other processes
- The output of Aircraft Scheduling feeds to Crew Scheduling, Revenue Management, MRO and Airport Operations
- The process of scheduling itself is divided in planning and operations stages
- Aircraft schedule planning often starts several months in advance and involves several steps
- On a broad level, the process is broken down into demand estimation, fleet assignment and tail number assignment in the sequence

Interface with Other Systems



Typical Schedule Development Process

Process	Strategic Planning	Long Term Scheduling	Intermediate Scheduling	Short Term Scheduling
Time	**6 months**	**6 - 4 months**	**4 -3 months**	**3 – 2 months**
Activity	• New Hubs •Fleet Planning •Acquisitions • Code sharing	•Market •Frequencies •Airport slots	•Fleeting •Crew Hour Planning • Robustness •Maintenance	•Maintenance •In Flight •Stations • Airport Slots •Reliability • Commercial
Models Used	• Profitability analysis • Code share analysis • Fleet planning	• Profitability analysis • Demand forecasting • Fleet Assignment	• **Fleet Assignment** • Re-Fleeting • Routing Model • Special events scheduling	• Through Assignment • **Routing Model** • Flight Number Continuity

Scheduling Process Stages

Schedule Design	Estimate itinerary level demands and identify suitable flight legs and time
↓ Fleet Assignment	Match demand with supply
↓ Aircraft Routing	Assign individual aircrafts to flight legs ensuring consistency and sequence
↓ Crew Pairing	Form sequence of flight legs satisfying human and labor work rules
↓ Crew Rostering	Assign crew (pilots and/or flight attendants) to flight duty sets

Aircraft Scheduling

Schedule Design	Estimate itinerary level demands and identify suitable flight legs and time
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Crew Scheduling

Schedule Design	Estimate itinerary level demands and identify suitable flight legs and time
Fleet Assignment	Match demand with supply
Aircraft Routing	Assign individual aircrafts to flight legs ensuring consistency and sequence
Crew Pairing	Form sequence of flight legs satisfying human and labor work rules
Crew Rostering	Assign crew (pilots and/or flight attendants) to flight duty sets

What is a Schedule?

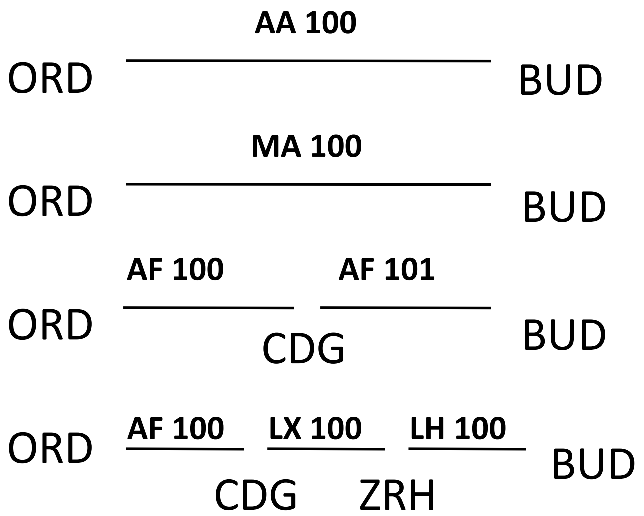
- Schedule is nothing but a time-table of all flights that the airline company intends to fly
- Typical information contained in a schedule is flight number, operating and marketing carrier, departure station, departure time (both local and a reference time), arrival station, arrival time (both local and a reference time), days of operation, schedule start and end dates, equipment flown etc.
- Standardization of schedules (called SSIM) is a generic way of airlines to share the schedules with travel agents

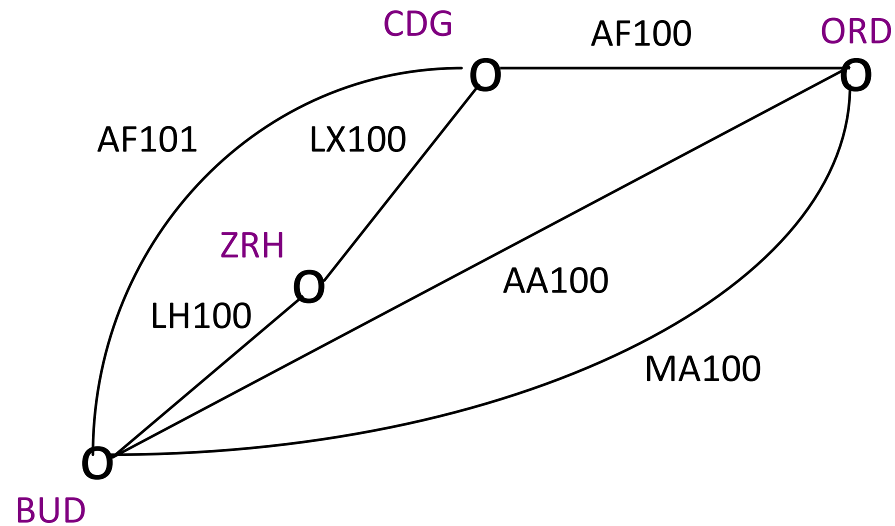
Schedule Design

- Multi-stage process. Usually uses the past or existing schedules as the most basic input. Individual flight and route performances in the light of existing and new competition is a major factor
- Analysts' *qualified* perceptions about the profitability and revenue potential on each flight is computed before adding or removing flights
- Sometimes a superset of all competing flights are fed into an optimization model to select the most profitable combination
- Profitability and potential revenues are computed by analysing the path preference and modeling the market share

Itinerary generation

Inputs: Schedule (also schedule for other airlines)





- Different criteria such as connection times, circuitry factor, flying time, etc.
- Online, code share, and interline itineraries
- Non-stop, one-stop, through, and two-stop connection itineraries

Market Share Modeling

Market share of a path on which booking is possible is determined by QSI model

Quality of Service index (QSI) is defined as a function of no. of stops, code-share flag, time of day preference, fare ratio relative to industry average, etc.

$$\text{Path Share}_i = \frac{SI_i}{\sum_j SI_j}$$

Demand Forecasting Steps

- Utilizes historical data for travel demand at true O&D level
- Time series forecasting with exponential smoothing is used to forecast
- Demands are allocated for all OD pairs, and traffic allocated by original QSI values
- Excess passengers are spilled. Spilled passengers are recaptured on itineraries with excess capacity using original QSI values
- This process is continued until all passengers are assigned or the spilled passengers cannot be recaptured on any of the itineraries
- Revenue = Demand * fare. OD level revenue is prorated to leg level

Fleet Assignment

- Now that the demand is known, the next step is to assign demand to supply
- Airline companies operate different types of aircraft fleets and sub-fleets (why?)

Fleet Assignment Motivation

Question:

Which aircraft (fleet) type should fly each flight?

Flight LX 100: ATR 72, Boeing 737, Boeing 767, or A320?

Assignment Profitability:

Given expected number of passengers on flight,

Aircraft too small ⇨ lost revenue

Aircraft too big ⇨ costly and inefficient

Problem Definition

<u>Given:</u>

- Flight Schedule
  - Each flight covered exactly once by one fleet type
- Number of Aircraft by Fleet Type
  - Limited by the availability, for each type
- Turn Times by Fleet Type at each Station
- Operating Costs, Spill and Recapture Costs, Total Potential Revenue of Flights, by Fleet Type

Problem Definition

<u>Objective:</u>

- Cost minimizing (or profit maximizing) assignment of aircraft fleets to pre-determined scheduled flights such that maintenance requirements are satisfied, conservation of flow (balance) of aircraft is achieved, and the number of aircraft used does not exceed the number available (in each fleet type)

<u>Constraints:</u>

- Maintenance check
- Crew block hours
- Gate, Noise
- Market
- Forced throughs, …

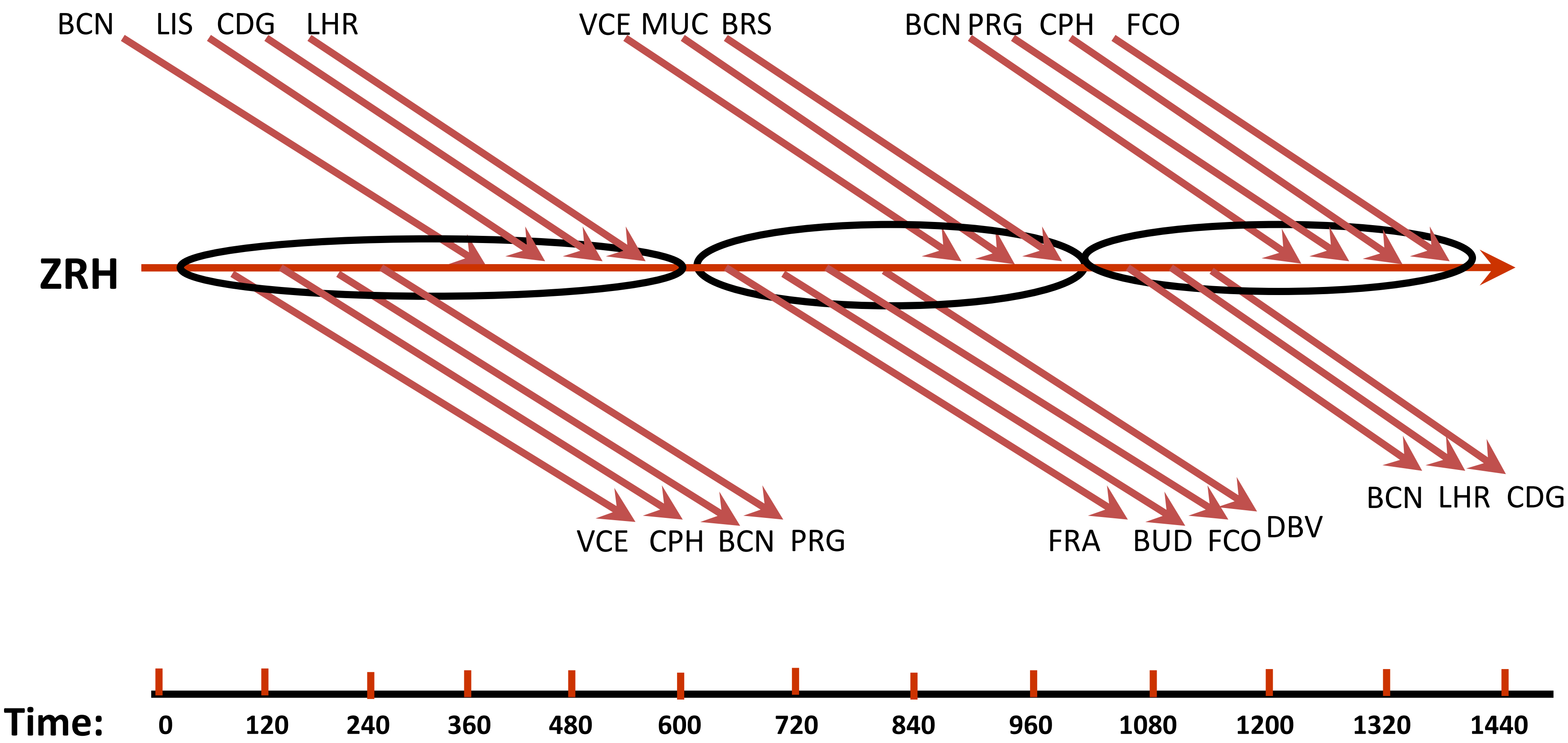
Terminology

- Spill
  - Passengers that are denied booking due to restrictions in capacity
- Recapture
  - Spilled passengers that are recaptured back to the airline from another travel itinerary
- For each itinerary, costs and revenues depend on fleet type of the relevant flights :
  - Total Cost = Operating cost + Spill cost
  - Total Revenue = Operating revenue + Recapture revenue

Network Representation

- Topologically sorted time-line network for a station-fleet pair
  - Nodes:
    - Bunch of flight arrivals/ departures over time for the station-fleet pair
  - Arcs:
    - Flight arcs: arcs represent scheduled flights
    - Ground arcs: allow aircraft to sit on the ground between flights

Network Representation



Fleet Assignment Model: Notations

- Sets
  - Set of fleets, indexed by k
  - Set of flights, indexed by f
  - Set of stations, indexed by s
  - Set of nodes, indexed by n
- Parameters
  - $Rev_{k,f}$ is the contribution of assigning fleet k to flight leg f
  - A_k is the number of available aircraft of fleet type k
  - $N_{k,s}$ is the last node of fleet k at station s
  - Number of planes of fleet type k into, out of node n and on air after last node are INTO(n), OUT OF(n) and ON_Air_k

Fleet Assignment Model: Notations

- Decision Variables
  - $x_{k,f}$ equals 1 if fleet type k is assigned to flight leg f, and 0 otherwise
  - $y_{k,s,n}$ is the number of aircraft of fleet type k, on the ground at station s, after node n
- Basic Constraints
  - Cover constraints: every flight must get assigned exactly one aircraft
  - Balance constraints: number of aircrafts of fleet type k arriving at a station must be same as those departing
  - Aircraft count constraints: cannot assign more aircrafts of each fleet type than available

Fleet Assignment Model

$$\text{Maximize} \sum_{k \in K} \sum_{f \in F} \text{Re}\, v_{kf} x_{kf}$$

Subject to:

$$\sum_{k} x_{k,f} = 1, \ \forall f \in F \qquad (1)$$

$$\sum_{f \in INTO(n)} x_{k,f} - \sum_{f \in OUTOF(n)} x_{k,f} + y_{k,s,n^-} - y_{k,s,n} = 0, \quad \forall n \in N, k \in K \qquad (2)$$

$$\sum_{f \in ON\_Air_k} x_{k,f} + \sum_{s,n \in N_{k,s}} y_{k,s,n} = A_k, \ \forall k \in K \qquad (3)$$

Bounds

$$0 \le x_{kf} \le 1, \ \text{binary} \quad \forall x_{kf}$$

$$0 \le y_{k,s,n} \le \# Arrivals_s$$

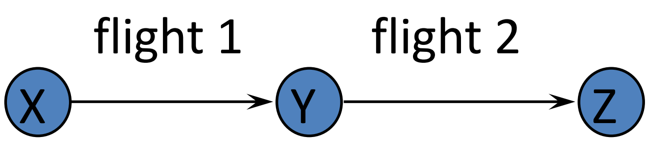
$y_{k,s,n}$ are defined as continuous, but will be integer

Fleet Assignment Model: Objective Function

- Revenue associated with assigning a fleet type *k* to a flight leg *f* is relatively straightforward to compute = average fare per passenger on *f* * MAX(number of seats on *k*, unconstrained demand for *f*)
- Lost revenue due to spilled pax for flight leg *f* and fleet assignment *k* = average fare per passenger on *f* * MAX(0, unconstrained demand for *f* – number of seats on *k*)
  - IATA suggests ground rules for revenue proration for inter-line itineraries (flown by multiple carriers), but can the same rule be used here?

Fleet Assignment Model: Objective Function

Fleet Type	Seats
α	50
β	100



Market	Itinerary	Average Fare	Pax Demand
X-Y	1	50 €	40
Y-Z	2	75 €	60
X-Z	1-2	100 €	40

- How can you use the above information of determine revenue contribution for a specific fleet choice for each leg?

Additional constraints

- Maintenance check constraint can be included in the model by replacing the following constraints instead of (2) and (3) in the model

$$\sum_{f \in INTO(n)} x_{k,f} - \sum_{f \in OUTOF(n)} x_{k,f} + y_{k,s,n^-} - y_{k,s,n} + \sum_{r \in IN(n)} m_{k,r,s} - \sum_{f \in OUT(n)} m_{k,r,s} = 0, \quad \forall n \in N, k \in K \qquad (4)$$

$$\sum_{f \in ON\_Air_k} x_{k,f} + \sum_{s,n \in N_{k,s}} y_{k,s,n} + \sum_{r,s \in Mtnc(k)} m_{k,r,s} = A_k, \quad \forall k \in K \qquad (5)$$

Additional constraints

- Market restriction constraint can be included in the model by defining the x_{kf} variables. If subfleet *k* is excluded from the market corresponding to flight *f*, $x_{kf} = 0$
- Station restrictions can be handled the same way
- Noise curfew restrictions are handled the same way. If subfleet *k* violates the noise curfew restriction at the origin or destination of flight *f*, $x_{kf} = 0$
- If the set $(f_1, f_2) \in ForcedThroughs$ represents all *throughs* that must be assigned the same aircraft type, the corresponding constraint is modeled as:

$$x_{kf_1} = x_{kf_2}, \quad (f_1, f_2) \in ForcedThroughs, \forall k \in K$$

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Fleet Assignment Model: Benefits

- Almost all big airline companies use fleet assignment models and have reported a positive impact on their bottom-line
- A large airline reported revenue increase of over 10 mil. € after the implementation of "basic" fleet assignment model, a revenue increment of 1.5%. This airline operated 18 different fleets and 3500 flights daily
- Airline fleet assignment model has a strategic dimension too as it can help monitor demand trends and provide inputs to new fleet acquisition teams

Fleet Assignment Model: Advancements

- Even though at the outset, we talk about the need to model spill and recapture in the fleet assignment. However the model proposed by us captures spill in multi-leg itineraries under certain assumptions while the recapture is not captured at all. That would bring us to the need to model fleeting at itinerary level instead of flight level and has been discussed in Lohanopanont and Barnhart (2004)
- Imagine a scenario where a particular fleet is not available for a flight, but a minor realignment of departure or arrival time by 5-10 mins provides a better solution. This is modeled in the generic fleeting model by incorporating time windows for every flight.

Trivia

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- Both of them operate fleets of several hundred aircrafts and both their revenues run into several billion dollars
- What else?

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- Of course, they both are Low Cost Airline companies – while Southwest is a leader in Americas, Ryan Air is a leader in Europe
- Both of them operate fleets of several hundred aircrafts and both their revenues run into several billion dollars
- $\mathbf{x_{737,f} = 1}$ (for Southwest)
- $\mathbf{x_{320,f} = 1}$ (for Ryan Air)

Maintenance Routing Problem

Problem Definition

- Given:
  - Flight Schedule with equipment type
    - Output of the Fleet Assignment Model
  - Number of Aircraft by Equipment Type
  - Aircraft Maintenance Requirements proposed by EASA etc
  - Turn Times at each Station
  - Costs for operating flights
  - Maintenance costs per aircraft

Problem Objective

- Determine the cost minimizing assignment of aircraft of a single fleet to scheduled flights such that each flight is covered exactly once, maintenance requirements are satisfied, conservation of flow (balance) of aircraft is achieved, and the number of aircraft used does not exceed the number available
- Alternatively, identify a set of feasible routes that a continuous succession of flights and maintenance opportunities such that maintenance check criteria are satisfied

Maintenance requirements

- "A" Checks
  - Maintenance required every 60 hours of flying
  - Only some station(s) will have the facility to maintain the aircraft
  - Maintenance itself could be carried out overnight
  - Airlines maintain aircraft more frequently than specified hours of flying, with an average of 40-45 hours of flying or even lower (why?)

Maintenance Constraints

- Maintenance arcs are usually represented for an aircraft as dummy flights that depart and arrive at the same station
- Each arc
  - begins at an aircraft arrival + turn time
  - spans minimum maintenance time
- While FAM identifies and assigns aircraft type at a global level, maintenance routing assigns specific tail number to each route. These routes are created in such a way so as to
  - ensure that sufficient maintenance opportunities exist
  - ensure that all aircrafts get equated maintenance opportunities

Network Representation

- We define a time-space connection network with
  - Nodes:
    - representing flight arrivals/ departures (time and space)
  - Arcs:
    - representing flight arcs: one arc for each flight
    - representing connection arcs: allow aircraft to connect between flights

Time-Space Connection Network: An Example

Flight Number	Origin	Destination	Departure Time	Arrival Time
101	GVA	VCE	06:00	07:00
111	GVA	LYS	06:30	08:00
152	GVA	FCO	07:30	09:30
102	VCE	GVA	11:45	13:00
201	FCO	ATH	11:55	12:45
211	LYS	FCO	13:30	14:15
301	LYS	ATH	16:00	18:30
213	FCO	LYS	16:30	18:15
112	LYS	GVA	19:30	21:00
400	ATH	GVA	21:30	00:30

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213	FCO	LYS	16:30	18:15
112	LYS	GVA	19:30	21:00
400	ATH	GVA	21:30	00:30

Maintenance Routing Model: String Model

- A string is a sequence of flights formed by linking feasible flight connections that can be operated by the same tail number. This string sequence takes care of maintenance requirement during its creation
- Note that the planning horizon is defined in advance. However the string formation need not be extended to the entire planning horizon as it can be repeatable over shorter durations. It is not necessary or desirable to form string for several weeks or months of flight schedule
  - Duration of string formation too long ⇨ complexity increases
  - Duration of string formation too short ⇨ sub-optimal solution
- If an airline has the same daily schedule, the planning horizon can potentially be one day, but it is desirable to plan this duration by taking into account the maintenance cost and duration

String Model: Constraints

- When constructing the strings, following constraints are ensured. Strings are constructed outside the mathematical model, usually with a separate piece of code
  - Maintenance constraints
    - Satisfied by variable definition
  - Cover constraints
    - Each flight must be assigned to exactly one string
  - Balance constraints
    - Needed only at maintenance stations
  - Fleet size constraints
    - The number of strings and connection arcs crossing the count time cannot exceed the number of aircraft in the fleet

Maintenance Routing Model: Notations

- Sets
  - Set of aircrafts in the fleet (P), indexed by p
  - Set of flights (F), indexed by f
  - Set of routes (R), indexed by r
- Parameters
  - c_r is the cost of flying route r
  - c_f is the cost of NOT flying flight f
  - $b_{r,f}$ is 1 if route r contains flight f, 0 otherwise
  - $b_{r,p}$ is 1 if route r is flown by aircraft p, 0 otherwise
- Decision Variables
  - x_r equals 1 if route r is selected, and 0 otherwise
  - y_f equal 1 if flight f is NOT covered, 0 otherwise

Maintenance Routing Model: Formulation

$$\text{Minimize} \sum_{r \in R} c_r x_r + \sum_{f \in F} c_f y_f$$

Subject to:

$$\sum_{r \in R} b_{r,f} x_r + y_f = 1, \ \forall f \in F \qquad (1)$$

$$\sum_{r \in R} b_{r,p} x_r \leq 1, \ \forall p \in P \qquad (2)$$

Bounds

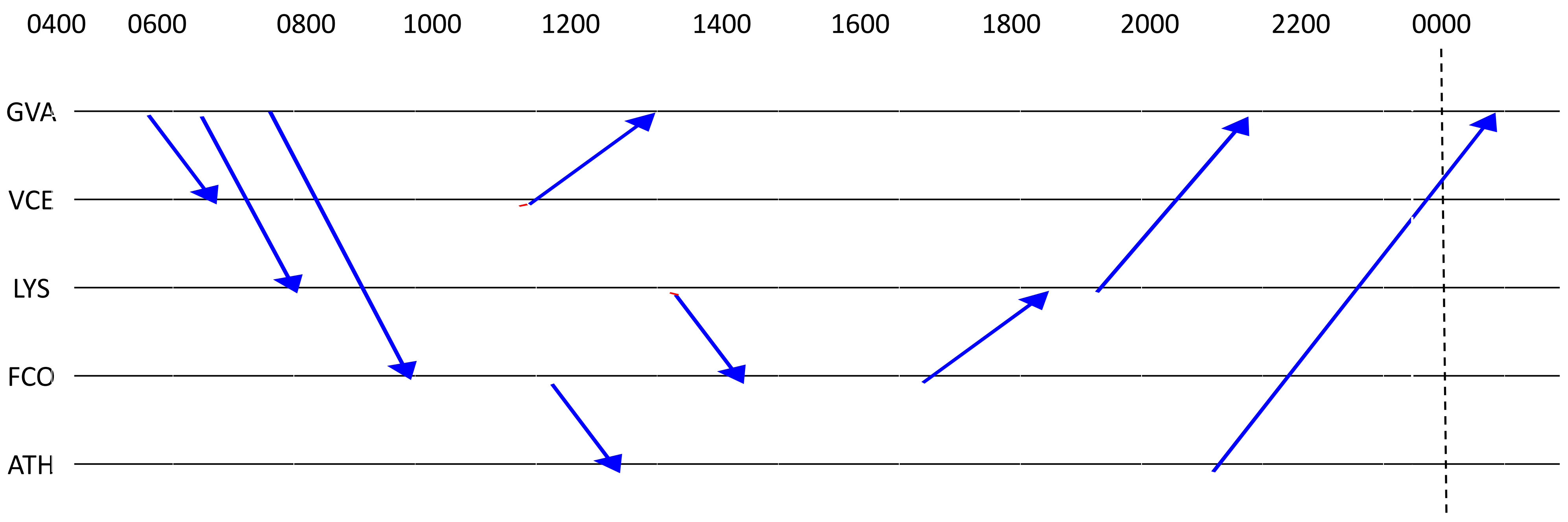
$$x_r \in \{0,1\}$$

$$y_f \in \{0,1\}$$

Solution Methodology

- Such problems can be solved using heuristics or using exact methods or as a hybrid of the two
- Heuristics usually work on intuition and thumb rules and can often provide fast and elegant solutions. For this problem, a good heuristic would be
  - Construct an initial solution covering all flight legs. This solution can be obtained using a greedy algorithm or improved using network flow shortest path problem for each satellite station to minimize costs
  - Swap aircrafts to improve solution and provide maintenance opportunities

Heuristic Example



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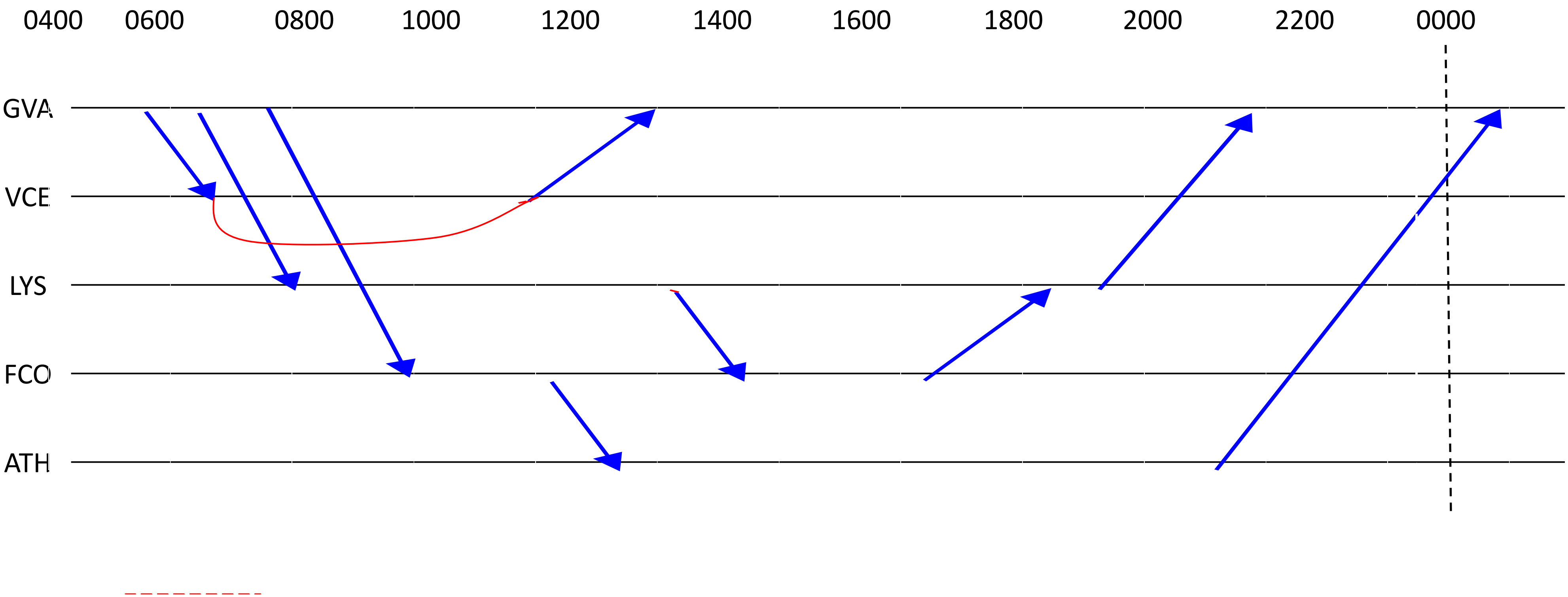

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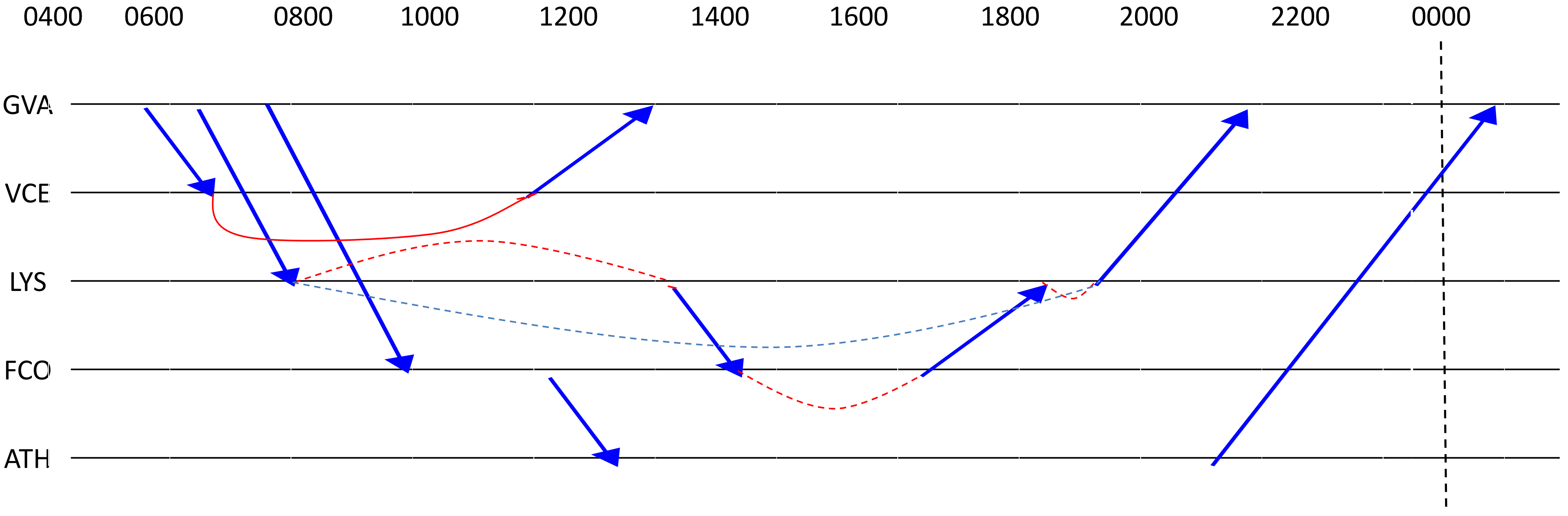

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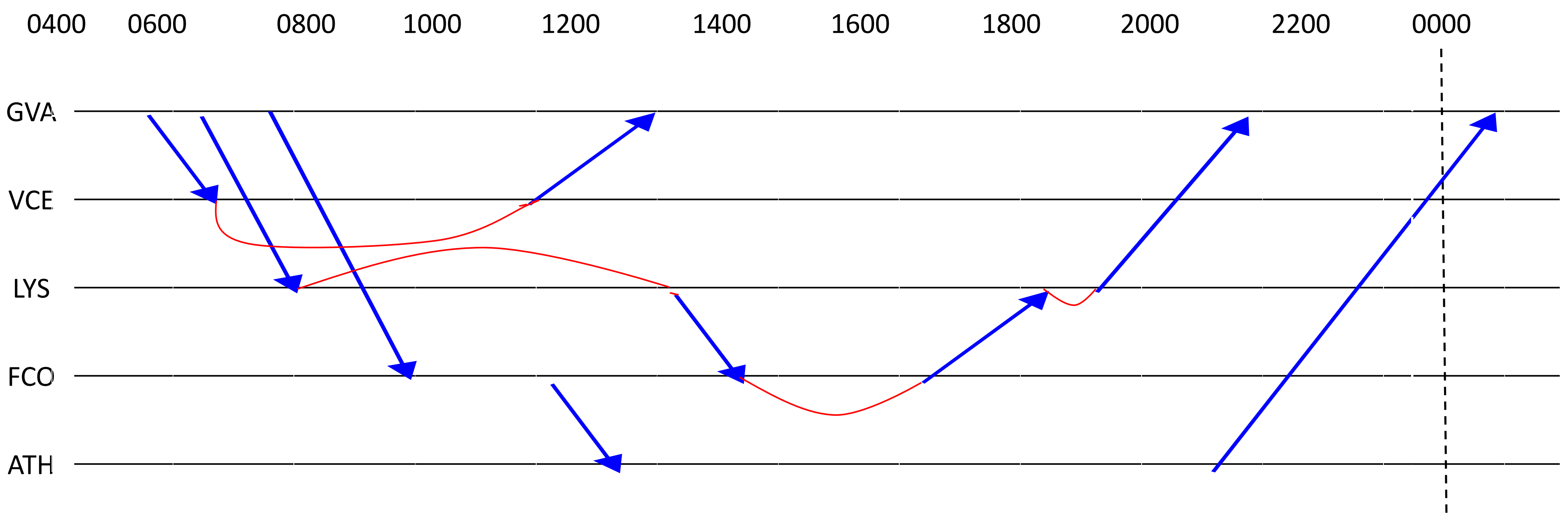

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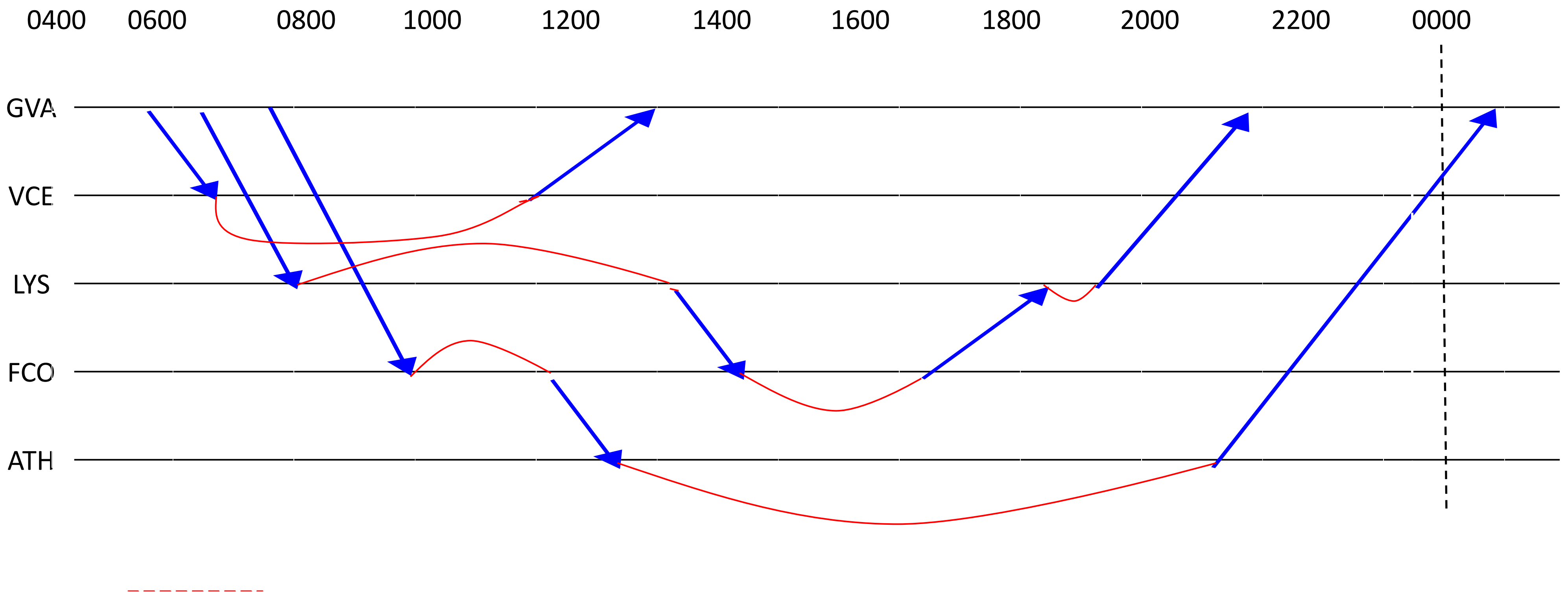

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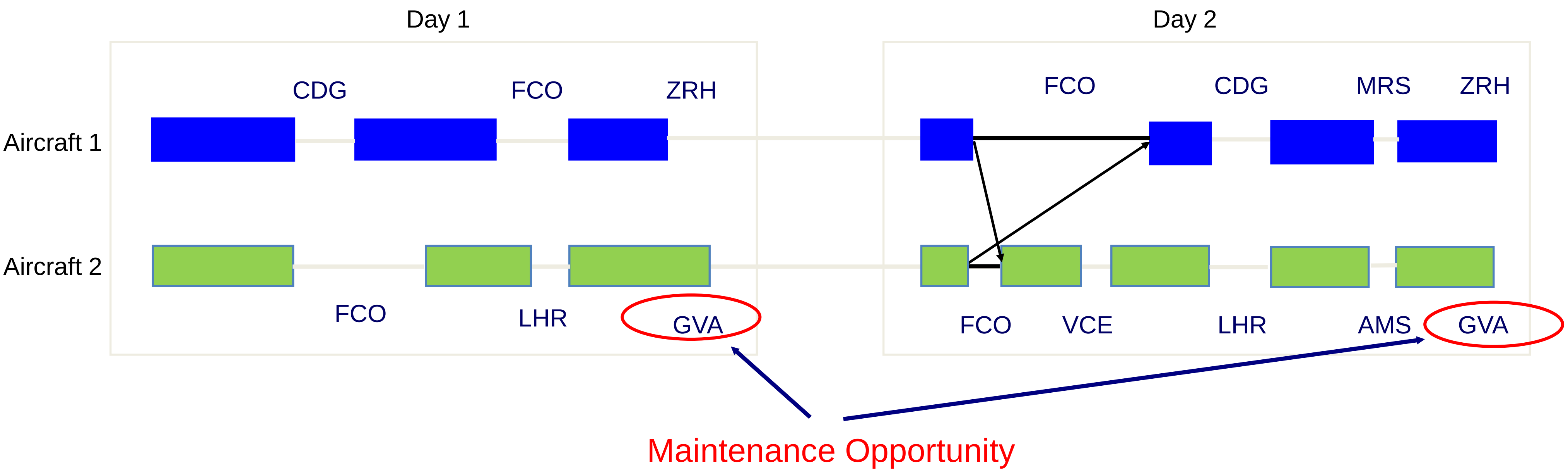
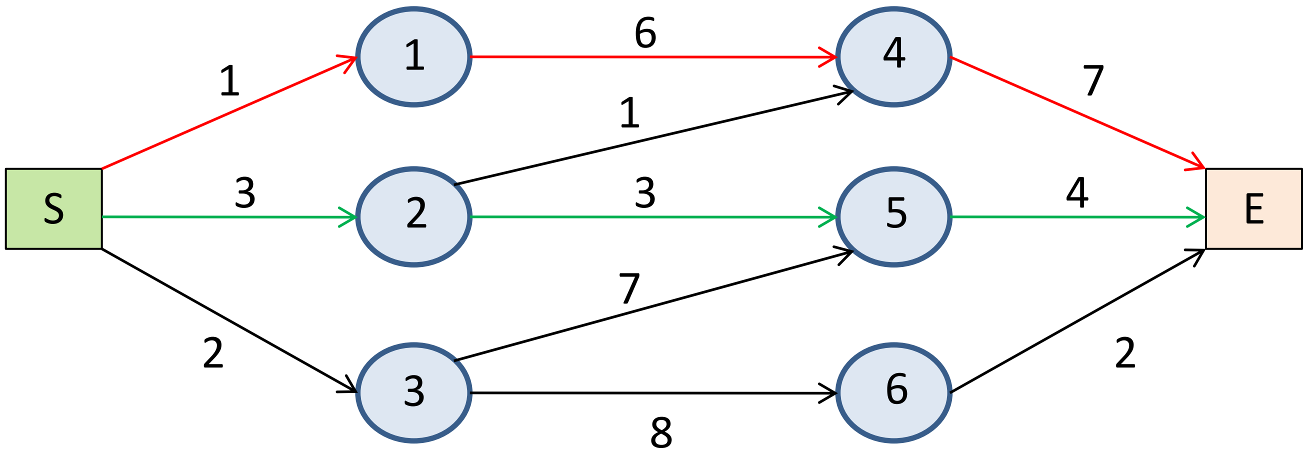


Heuristic Limitations

- Most heuristics or thumb-rules lack “clairvoyance”
- They cannot optimize beyond the current situation and thus end up with sub-optimal (often, highly sub-optimal) solutions
- Example of the shortest path problem below. If start from the shortest path to the next link, we could end up with the longest path



Heuristic Limitations

- Another major concern with using heuristics is that we do not know how far we are from the “true” optimal solution
- For one problem instance, we may be within 5% of optimality, while in another situation we could be 140% away from optimality
- This impacts the benchmarking process and does not help us measure the efficiency or effectiveness of a heuristic

Review

- We learnt about the different aircraft scheduling models
- We learnt to formulate these sub-problems into mathematical models
- We learnt to solve certain problems with heuristics
- However for the problems learnt today, heuristics do not perform well
- So in the next class, we will learn solving these problems with alternative (hopefully, better!) methods